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3.	Full name, address and postcode of the or of each applicant *(underline all surnames)* Patents ADP number *(if you know it)* If the applicant is a corporate body, give the country/state of its incorporation	Filtronic Compound Semiconductors Limited The Waterfront Salts Mill Road Saltaire Shipley West Yorkshire BD18 3TT UNITED KINGDOM 8406738001
4.	Title of the invention	A MICRO-ELECTROMECHANICAL VARIABLE CAPACITOR
5.	Name of your agent *(if you have one)* "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)* Patents ADP number *(if you know it)*	Marks & Clerk 43 Park Place Leeds LS1 2RY 18013
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Continuation sheets of this form	-
Description	7
Claim*(s)*	4
Abstract	1
Drawing*(s)*	3

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A MICRO-ELECTROMECHANICAL VARIABLE CAPACITOR

The present invention relates to a micro-electromechanical (MEM) variable capacitor and a method for fabricating the same.

MEM variable capacitors are expected to be particularly suitable in microwave and millimetre wave applications such as, for example, tunable filters and voltage controlled oscillators where a high quality factor (Q) and a wide tuning range are desirable.

A MEM variable capacitor comprises a pair of electrodes: a fixed electrode that is mounted on a substrate and a movable electrode that is suspended over the fixed electrode to define an air gap between facing planar surfaces of the electrodes. When a DC control voltage is applied across the electrodes the moveable electrode moves toward the fixed electrode under electrostatic attraction. This reduces the air gap between the electrodes and increases the capacitance. The motion of the moveable electrode is restricted by a mechanical spring force. The spring force is directly proportional to the distance travelled by the moveable electrode (i.e. the reduction in the original air gap) whereas the electrostatic attractive force has a non-linear relationship with the air gap.

It can be shown mathematically that when the air gap is less than two-thirds of the initial air gap distance the electrostatic attractive force exceeds the spring force and the electrodes are pulled together. The control voltage at which this occurs is known as the "pull-in" voltage. This limits the capacitance tuning ratio to 1.5:1 which is inadequate for many applications.

Even to achieve a tuning ratio of 1.5:1 requires the operation of the device at voltages close to the pull-in voltage and therefore it is often the case that pull-in occurs. When this happens the facing planar surfaces come into contact with each other and often adhere together after the applied voltage has been removed as a result of stiction. This results in device failure. Stiction between the facing planar surfaces also leads to low yields when such devices are being fabricated

One known approach to improving the capacitance ratio of a MEM variable capacitor is disclosed in WO 01/61848. As in the device described above a moveable

electrode is anchored at each end so as to be suspended above a fixed electrode but is flexible so that it deflects when the control voltage is applied. The fixed electrode is, however, split such that there is a central active electrode that combines with the movable electrode to form the variable capacitor and two outer control electrodes to which the control voltage is applied. The central electrode is located midway between the anchors where the deflection of the flexible electrode is greatest. The electrodes are arranged so that the gap between the central electrode and the flexible electrode is less than that between the control electrodes and the flexible electrode. In operation, the maximum deflection of the flexible electrode is limited by the distance between it and the control electrodes. The minimum distance between the deflected flexible electrode and the control electrodes to avoid pull-in is again two thirds of the initial gap. If the gap between the central electrode and the flexible electrode is made less than one third of that between the control electrodes and the flexible electrode then the pull-in voltage does not limit the tuning range.

The device described in WO 01/61848 does provide a wider tuning ratio range, but pull-in still occurs in some circumstances and stiction resulting in device failure is therefore still a problem during both use and manufacture.

A paper published after a conference in San Francisco 10-13 December 2000 (Development of a Wide Tuning Range MEMS Tunable Capacitor for Wireless Communication Systems, Jun Zou; Chang Liu; Schutt-Aine,J; Jinghong Chen, and Sung-Mo Hung 0-7803-6441-4/00) describes the performance of a device of the same general type as that described in WO 01/61848. The paper notes that, in a test device, after pull-in had occurred the spacing between the facing surfaces could not be reduced to zero, suggesting by way of explanation "Possible reasons are surface roughness of the two plates, the existence of residual film from sacrificial layer etching, or absolute measurement calibration." The same paper also refers to the achievable tuning range value being dependent upon "other factors, such as surface roughness and curvature." The facing surfaces of the capacitor plates are however fabricated using a process which relies upon the deposition of layers of material by thermal evaporation which will, if performed successfully, result in smooth surfaces

and thus references to "roughness" in the paper are concerned with manufacturing errors rather than a deliberate attempt to achieve a surface which is not smooth.

It is an object of the present invention to obviate or mitigate the problems outlined above.

According to a first aspect of the present invention there is provided micro-electromechanical variable capacitor comprising first and second capacitor plates defining facing surfaces which are spaced apart to define a gap, and means for applying a potential difference across the gap, at least one of the plates being movable relative to the other such that when a potential is applied across the gap the width of the gap is varied as a function of the applied potential so as to vary the capacitance of the capacitor, wherein the facing surface of at least one plate has a roughened surface, the degree of roughness being sufficient to prevent the facing surfaces adhering together.

The means for applying a potential difference may be configured to apply the potential difference across the facing surfaces of the plates. Alternatively, the first capacitor plate defines at least one control electrode and the means for applying a potential difference is configured to apply the potential difference across the (or each) control electrode and the second plate.

The first capacitor plate may define an active electrode on which said facing surfaces is defined. The gap between the active electrode and the second capacitor plate is ideally less than that between the (or each) control electrode and the second capacitor plate. The active electrode is preferably disposed between two control electrodes and ideally in a central position.

The second capacitor plate may be movable and the first capacitor plate fixed. The second plate is preferably flexible and is movable by virtue of its flexibility. Preferably the second plate comprises a pair of anchor members that are fixed relative to the first plate and an intermediate portion that is flexible and moveable. The intermediate portion of the second plate is substantially planar.

The facing surface of the first plate has a roughened surface and/or the facing surface of the second plate has a roughened surface.

The first plate may be fixed to a substrate.

At least the facing surface of the (or each) plate with a roughened surface is fabricated from any metal using an electroplating process such as, for example, electroplating nickel.

At least the facing surface of the active electrode is ideally fabricated by electroplating.

According to a second aspect of the present invention there is provided a method for fabricating a micro-electromechanical variable capacitor having first and second capacitor plates defining facing surfaces which are spaced apart to define a gap, and means for applying a potential difference across the gap, at least one of the plates being movable relative to the other such that when a potential is applied across the gap the width of the gap is varied as a function of the applied potential so as to vary the capacitance of the capacitor, the method comprising the step of fabricating at least one plate with a roughened facing surface, the degree of roughness being sufficient to prevent the facing surfaces adhering together.

Preferably the method further comprises the steps of fabricating the first plate with a roughened surface, fabricating an overlying intermediate layer such that the roughness of the facing surface is repeated on an upper surface of the intermediate layer and then fabricating the second plate over the intermediate layer such that its facing surface is formed with an inverse of the upper surface of the intermediate layer, and then removing the intermediate layer.

At least the facing surface of the first plate may be fabricated by electroplating and/or at least the facing surface of the second plate may be fabricated by electroplating.

The intermediate layer may be removed by etching. In one embodiment the intermediate layer is fabricated from titanium.

A specific embodiment of the present invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 is a schematic representation of the variable capacitor of the present invention;

Figure 2 is a schematic representation of the capacitor of figure 1 shown with an upper electrode deflected;

Figures 3a to 3g illustrate the steps in fabricating the capacitor of the present invention.

Figure 4 is a microscope image of the variable capacitor of the present invention; and

Figure 5 is a graph illustrating the variation in capacitance against bias voltage.

Referring first to figures 1 and 2 of the drawings, the illustrated micro-electromechanical capacitor is fabricated on a substrate 1 and has a pair of spaced capacitor plates in the form of an upper electrode 2 suspended over a lower electrode 3 so as to define an intermediate air gap 4. The lower electrode 3 is formed on the substrate 1. The electrodes 2 and 3 together define a variable capacitor as represented by the symbol labelled 5.

The lower electrode 3 is disposed between a pair of outer bias electrodes 6. The electrode 3 is thicker than the bias electrodes 6 so that the air gap 4 between the upper and lower electrodes 2,3 is smaller than the gap between the upper and bias electrodes 2, 6.

The upper electrode 2 is anchored at each end but is flexible so that it may deflect relative to the substrate 1. When a DC voltage V is applied between the upper and bias electrodes 2, 6, electrostatic attraction causes the upper electrode 2 to deflect downwardly towards the lower electrode 3 as is illustrated in figure 2. This reduces the air gap 4 and thereby increases the capacitance. The bias voltage is changed to vary the amount of deflection and therefore the capacitance value.

The lower surface 7 of the upper electrode 2 and the upper surface 8 of the lower electrode 3 are roughened by methods that will be described below. The roughened surfaces reduce the tendency for stiction, thereby improving the reliability of such capacitors.

Figures 3a to 3g illustrate the fabrication process of the variable capacitor. First, 0.03μm of nickel 10 is e-beam evaporated on to a clean silicon substrate 1 and patterned by conventional photoresist deposition/exposure techniques to form bases for the lower electrode 3, the bias electrodes 6 and anchor pads 11 for the upper electrode 2 (figure 3a). A 0.2μm layer of titanium 12 is then deposited using e-beam

evaporation (figure 3b) and a hole is etched through the titanium to the nickel layer forming the base for the lower electrode 3. Using a nickel sulfamate based electroplating bath, 0.2μm of nickel is then electroformed into the hole to create the thick lower electrode 3 (figure 3c). The evaporated nickel at the base of the hole acts as a seed layer for the electroplating. By controlling the electroplating current density, a roughened surface finish 13 is applied to the thick lower electrode 3. A further 0.1μm of titanium 14 is then e-beam evaporated (figure 3d). It is this layer that defines the spacing between the central electrode 3 and the upper electrode of figures 1 and 2.

Holes are etched above the anchor pads 11, and the holes are filled with 0.3μm of nickel 15 by electroforming (figure 3e). A further 0.3μm of nickel 16 is added across the full width of the structure by electroplating (figure 3f). The electroplated nickel 15 previously deposited over the anchor pads 11 and the evaporated titanium 14 both serve as an electroplating seed. This nickel layer 16 forms the upper electrode 2. The titanium layer 14 is such that the roughness of the surface of the lower electrode 3 is propagated through to succeeding layers. Thus the upper surface of the titanium layer 14 has the same roughness in the region directly over the central electrode 3 as the surface 13 of the lower electrode 3 and this roughness is carried through (in complementary form) to the underside of the subsequent electroplated nickel 16. Finally, the titanium layer 14 is etched by hydrofluoric acid solution followed by rinsing in isopropyl alcohol that is allowed to evaporate at 90^0 to leave the air gap 4 between the upper 2 and lower electrodes 3 and a wider gap between the upper electrode 2 and the bias electrodes 6.

An image of the fabricated capacitor from above is shown in figure 4. It can be seen that the topography of the initially deposited nickel portion (figure 3a) has carried through to the upper surface of the upper electrode 2. The graph shown in figure 5 indicates the results of tests using a Boonton 72BD digital capacitance meter with a signal frequency of 1MHz. For a DC bias voltage of 0V to 12V the measured capacitance ranges from 0.7pF to 3.6pF. This corresponds to a tuning ratio of 5.1:1. Moreover, the tendency for stiction between the plates is significantly reduced.

It will be appreciated that numerous modifications to the above described design may be made without departing from the scope of the invention as defined in

the appended claims. For example, the roughened surface may be present on one or other of the central electrode or the underside of the upper electrode rather than both. Any process other than electroplating which results in the required roughness may be used. Moreover, the intermediate (sacrificial) layer between the central and upper electrodes may be fabricated from any suitable material other than titanium. If both electrodes are required to have a roughened surface then the material used should be non-planarising i.e. any roughness on the surface of the central electrode should be carried through to the upper surface of the intermediate layer. The invention may also be applied to a device in which the control voltage is applied between the two electrodes which are used to define the capacitor rather than as described above in which the control voltage is applied between one of those electrodes and a bias electrode.

CLAIMS

1. A micro-electromechanical variable capacitor comprising first and second capacitor plates defining facing surfaces which are spaced apart to define a gap, and means for applying a potential difference across the gap, at least one of the plates being movable relative to the other such that when a potential is applied across the gap the width of the gap is varied as a function of the applied potential so as to vary the capacitance of the capacitor, wherein the facing surface of at least one plate has a roughened surface, the degree of roughness being sufficient to prevent the facing surfaces adhering together.

2. A micro-electromechanical variable capacitor according to claim 1, wherein the means for applying a potential difference is configured to apply the potential difference across the facing surfaces of the plates.

3. A micro-electromechanical variable capacitor according to claim 1, wherein the first capacitor plate defines at least one control electrode, the means for applying a potential difference being configured to apply the potential difference across the (or each) control electrode and the second plate.

4. A micro-electromechanical variable capacitor according to claim 3, wherein the first capacitor plate defines an active electrode on which said facing surfaces is defined.

5. A micro-electromechanical variable capacitor according to claim 4, wherein the gap between the active electrode and the second capacitor plate is less than that between the (or each) control electrode and the second capacitor plate.

6. A micro-electromechanical variable capacitor according to claim 4 or 5, wherein the active electrode is disposed in between two control electrodes.

7. A micro-electromechanical variable capacitor according to any preceding claim, wherein the second capacitor plate is movable and the first capacitor plate is fixed.

8. A micro-electromechanical variable capacitor according to claim 7, wherein the second plate is flexible and is movable by virtue of its flexibility.

9. A micro-electromechanical variable capacitor according to claim 8, wherein the second plate comprises a pair of anchor members that are fixed relative to the first plate and an intermediate portion that is flexible and moveable.

10. A micro-electromechanical variable capacitor according to claim 9, wherein the intermediate portion of the second plate is substantially planar.

11. A micro-electromechanical variable capacitor according to any preceding claim, wherein the facing surface of the first plate has a roughened surface.

12. A micro-electromechanical variable capacitor according to any preceding claim, wherein the facing surface of the second plate has a roughened surface.

13. A micro-electromechanical variable capacitor according to any preceding claim, wherein the first plate is fixed to a substrate.

14. A micro-electromechanical variable capacitor according to any preceding claim, wherein at least the facing surface of the (or each) plate with a roughened surface is fabricated by electroplating with a metal.

15. A micro-electromechanical variable capacitor according to claim 14, wherein at least the facing surface of the (or each) plate with a roughened surface is fabricated from electroplated nickel.

16. A micro-electromechanical variable capacitor according to any one of claims 4, 5 or 6, wherein at least the facing surface of the active electrode is fabricated by electroplating.

17. A method for fabricating a micro-electromechanical variable capacitor having first and second capacitor plates defining facing surfaces which are spaced apart to define a gap, and means for applying a potential difference across the gap, at least one of the plates being movable relative to the other such that when a potential is applied across the gap the width of the gap is varied as a function of the applied potential so as to vary the capacitance of the capacitor, the method comprising the step of fabricating at least one plate with a roughened facing surface, the degree of roughness being sufficient to prevent the facing surfaces adhering together.

18. A method according to claim 17, wherein at least the facing surface of the first plate is fabricated by electroplating.

19. A method according to claim 17, wherein at least the facing surface of the second plate is fabricated by electroplating.

20. A method according to claim 17, 18 or 19, further comprising the steps of fabricating the first plate with a roughened surface, fabricating an overlying intermediate layer such that the roughness of the facing surface

is repeated on an upper surface of the intermediate layer and then fabricating the second plate over the intermediate layer such that its facing surface is formed with an inverse of the upper surface of the intermediate layer, and then removing the intermediate layer.

21. A method according to claim 20, wherein said intermediate layer is removed by etching.

22. A method according to any one of claims 20 or 21, wherein the intermediate layer is a sacrificial layer fabricated from titanium.

23. A method according to claim any one of claims 17 to 22, wherein the first capacitor plate is fabricated to have at least one control electrode, the means for applying a potential difference being configured to apply the potential difference across the (or each) control electrode and the second plate.

24. A method according to claim 23, wherein the first capacitor plate is fabricated to have an active electrode on which said facing surface is defined

25. A micro-electromechanical variable capacitor substantially as hereinbefore described with reference to the accompanying drawings.

26. A method for fabricating a micro-electromechanical variable capacitor substantially as hereinbefore described with reference to the accompanying drawings.

ABSTRACT

A MICRO-ELECTROMECHANICAL VARIABLE CAPACTITOR

A micro-electromechanical variable capacitor with first and second capacitor plates spaced apart to define a gap therebetween. The first plate has two control electrodes an active electrode. The second plate is movable relative to first plate when a voltage is applied to produce a potential difference across the control electrode and the second capacitor plate. This has the effect of varying the capacitance of the capacitor. The facing surface of at least one of the plates is formed in such a way that it has a roughened surface. The degree of roughness is sufficient to prevent the facing surfaces adhering together through stiction.

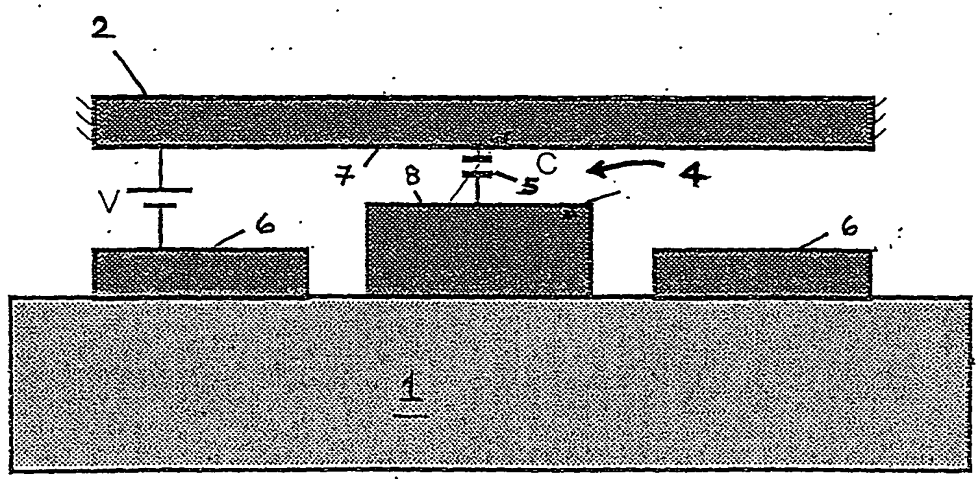

FIG. 1

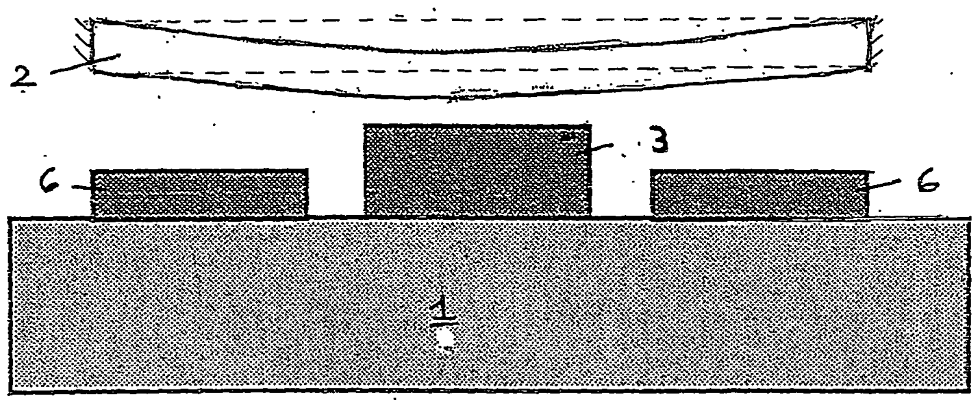

FIG. 2.

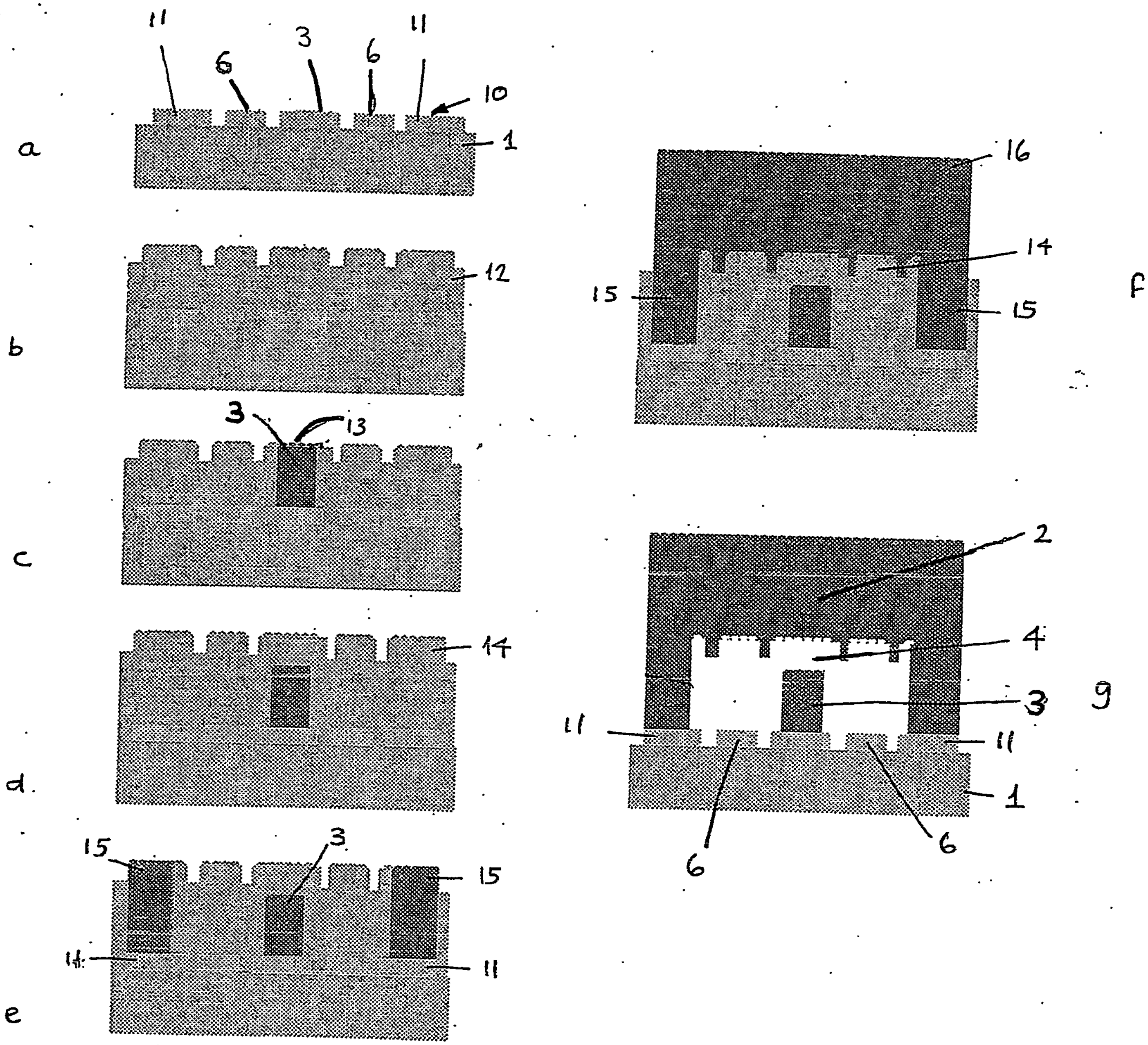

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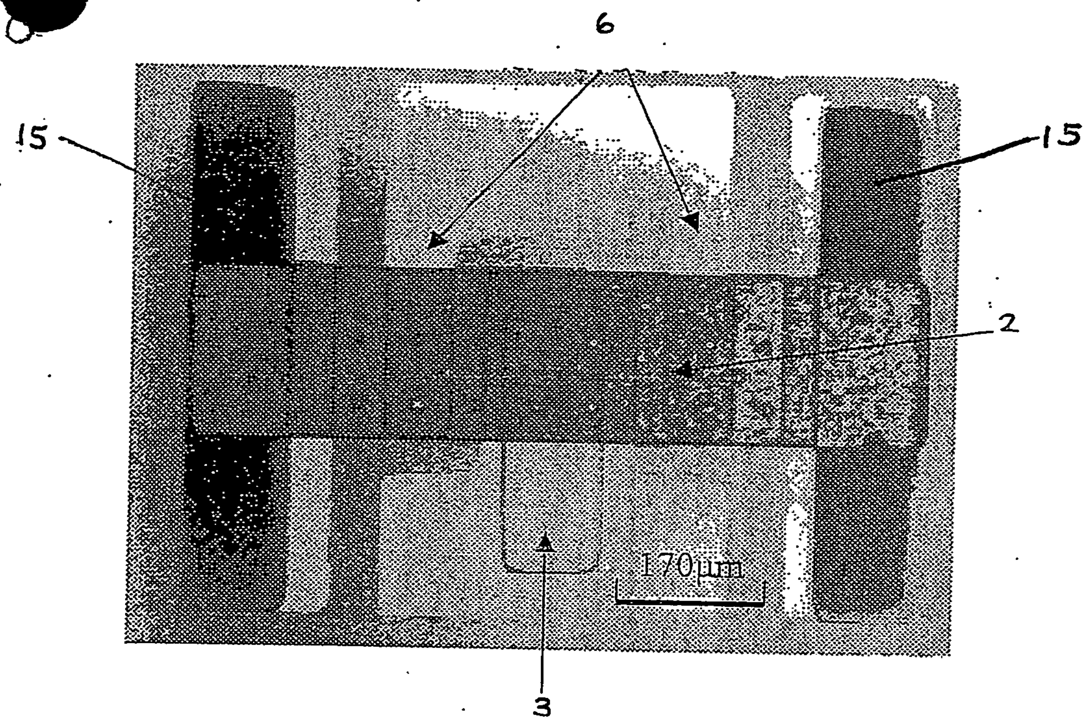
FIG. 3.

Figure 4



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